# Compressed Air Energy Storage (CAES) for Agricultural Applications

## Interim Report for Colorado Department of Agriculture

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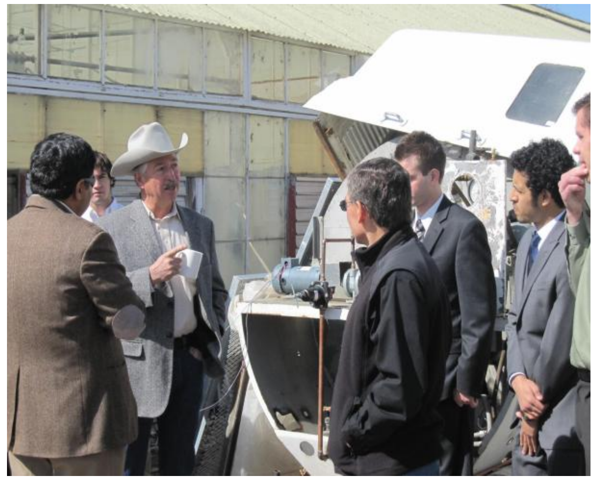
## Introduction

This report documents iCAST's progress to date on the research of Compressed Air Energy Storage (CAES) technology within agricultural applications for the ACRE grant funded by the Colorado Department of Agriculture.



John Salazar reviewing the project team's 1,000 Gallon CAES Prototype at CSU

The primary goal of this project is to provide agricultural producers the best energy storage solution that will maximize the benefits of generating their own energy from various renewable energy systems. Without an energy storage device, producers are forced to sell their renewable energy at very low prices to their utility and then have to buy energy from the utility at a much higher rate. The ideal storage system will provide a producer the option of using the energy from their own renewable energy system when needed and/or sell their excess energy to the utility for a profit during the utility's peak load.

## Work Completed to Date

To date iCAST has developed a project team with backgrounds including Engineering, Business, Finance, and Agriculture backgrounds. The team draws from iCAST staff, industry experts, and Professors and students from both the Colorado School of Mines and Colorado State University. The project team has successfully completed a 1,000 gallon prototype CAES system located on the CSU campus greenhouse site capable of storing and providing 320 Watts of power for 15 minutes. The prototype proved that a CAES on an agriculture application is technically feasible; however there were significant inefficiencies within the system making the system financially inefficient. The team also completed an initial report (Appendix A) which highlights the prototype's design, calculations, and conclusions. Lastly the team has begun to improve the system efficiencies and improve upon the prototype design in an effort to optimize the system and make it as efficient as possible so as to improve its financial viability.

## Preliminary Findings & Key Accomplishments

The preliminary findings show that a CAES is technically feasible in an agriculture application however the initial design proved to have an efficiency of 2.75%. With such a low efficiency, the design proved to be technically feasible and financially unfeasible. An overview of project findings can be found in Appendix A.

## Problems Encountered and/or Mitigating Circumstances

**Efficiency**

With the efficiency of 2.75% the team expects to improve the efficiency of the overall system by redesigning the system, increasing the scale of the system and by using higher efficiency components.

Air Motor and front side of the 1,000 gallon CAES Prototype

**Safety**

Safety concerns must be addressed with a larger storage tank. While using a larger storage tank there are higher air pressures flowing in and out of the system. There are large temperature differences between the higher temperature of air stored in the storage tank and very low temperature (up to -200 F) of the high pressure air flushed out of the system.

**Temperature / Freezing**

To maintain higher efficiencies of the system, the air to be stored inside the storage tank needs to be de-hydrated first before storing it in the storage tank. This helps avoid the system from freezing and eventually breaking down completely.

**Noise**

With the current design, we have observed that the CAES system is very noisy while storing the air in the Storage Tank and also while generating power, which will require sound proofing for noise reduction.

## Next Steps

The next steps of the project are to research and design a more efficient CAES system. The following issues will be addressed and included in the final design.

- Need to achieve higher efficiency of at least over 16% to make the system viable to use over long period of time and improve Rate of Return.
- Need to procure cheaper storage tank, e.g. a 30,000 gallon tank.
- Need to address the issue of wide temperature differences between outside ambient air, air in the tank and the temperature of the air flowing out of the tank while generating power.
- Need to use an electronic controller to improve the operation of the overall system, while improving the overall efficiency of the system
- Need to address important Safety parameters
- Need to make the system fully autonomous.

Process Flow Diagrams (PFDs) have been developed to show process flows, major equipment and significant control loops. The PFDs are documented in Appendix B. Piping and Instrumentation Diagrams (P&IDs) will be developed to show preliminary piping sizes, major and minor equipment and any control loops.

Attempts will be made to obtain +/- 20% quotes on all major equipment. If equipment quotes cannot be obtained, then equipment will be priced by size using factors from literature.

All electrical consumed or generated will be assumed to be 460 V, 3 phases and 60 hertz.

Since there are a number of utility companies in the state of Colorado, it is impractical to determine the cost of the peak and non-peak power cost for each one. The economics of the CAES project will be preformed on a basis of using a differential between peak and off peak power cost. Economics calculations will be determined for a break-even cost and multiple Rates of Return (ROR).

## Anticipated Changes to Timeline

At this time there is a possibility that the project team may complete the project prior to the contractual completion date of 10/31/2012.

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# Compressed Air Energy Storage System

## MECH 486-Senior Design Final Report

**May 29 2011**

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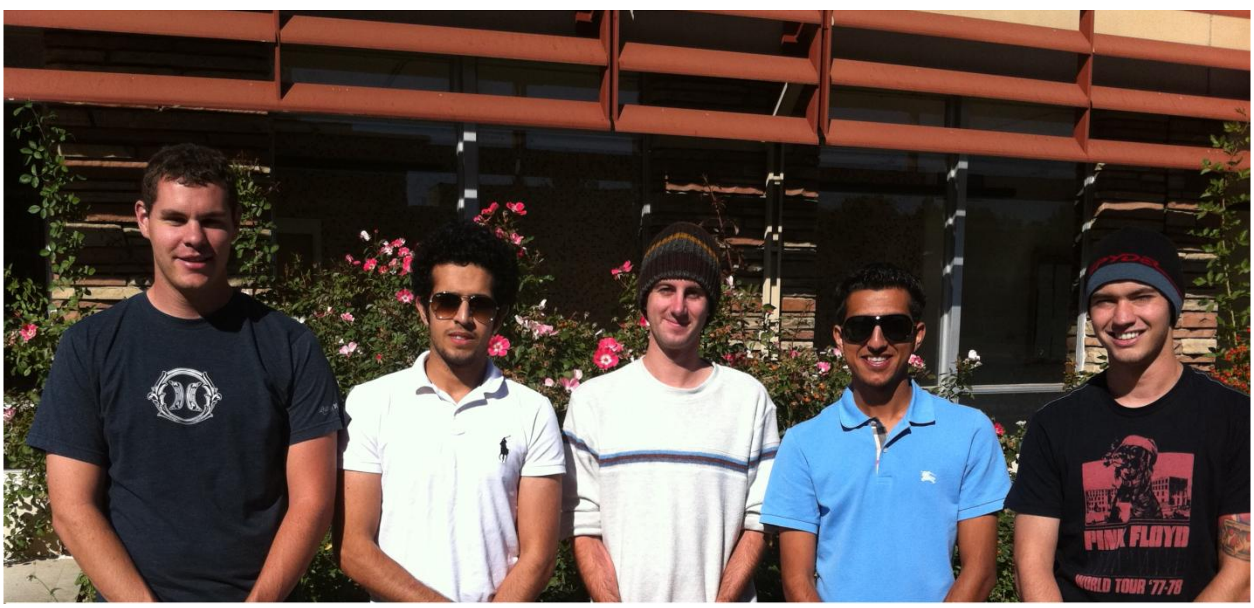


2010 iCAST Group Members

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# Introduction:

This project will be the implementation of a Compressed Air Energy Storage (CAES) system installed at the CSU greenhouse. A pneumatic compression and generation system will be put in place to evaluate the fiscal feasibility of the CAES system.

As environmental concerns continue to grow and energy/oil costs rise, the demand and need for renewable energy continues to grow. The lack of a practical and economically viable means of storing the produced energy continues to hamper the growth of renewable energy. This energy in not always produced when desirable so the ability to store that energy until needed is the main factor in the production.

Previous International Center for Appropriate & Sustainable Technology (iCAST) groups have researched the best renewable energy system for storage and have shown that a CAES system was the most satisfactory project to achieve scalability, ease of implementation, availability and cost. The initial design and mock control system has already been developed and testing has been done with a system containing a tesla turbine and alternator. The ideal system will provide the option to either use the stored energy to power loads or sell excess/stored energy back to the utility during peak load. The agricultural audience has been extremely positive to this concept which has led to the continued research and production of a larger scale CAES system.

The prototype from last year is a small scale demonstration of the CAES system producing enough power to run a 60W light bulb series with a 33 gallon storage tank for approximately 50 seconds. The prototype incorporated a heat recovery to aid in the expansion cycle which will not be included in this year's pilot. This year's team evaluated this project and found some safety issues that will be remedied in the pilot. Safety will be a major element since the pilot will be scaled up; pressures and loads will be increased and procedures need to be put in place to insure proper protection. Any applicable code or specification that is relevant to the CASE project will be followed.

**Figure 1.1:**2009 iCAST CAES small scale prototype

Huntorf is a large scale CAES system which is in operation in Germany that can produce 290 MW by pressurizing salt caverns at up to 1100 psi. This year's team is attempting to bridge the gap between these two and design a medium size system capable of performing some of the intermediate tasks which would require .3-1kW.

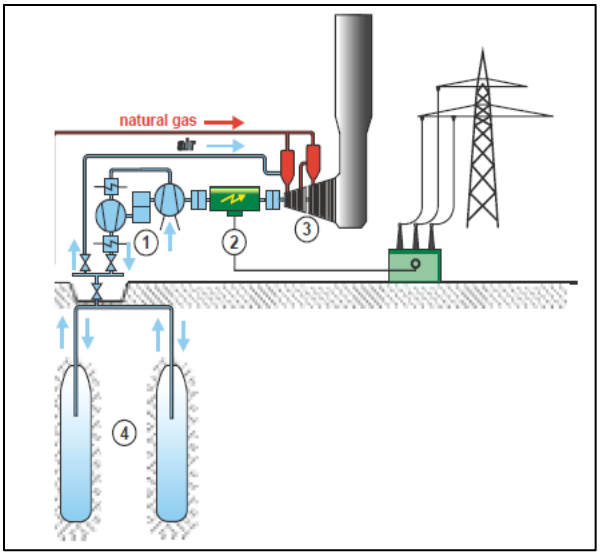


**Figure 1.2**: Huntorf plant consisting of (1) compressor train, (2) motor-generator unit, (3) gas turbine and (4) underground compressed air storage

There is also a McIntosh plant in Alabama that is modeled after Huntorf but made improvements by incorporating a recuperator to preheat air with waste heat from the turbines. This reduced fuel costs by as much as 25%. The Mclntosh and Huntorf plant are much too large for the project the team is working on but something can be looked to model after. The Mclntosh is rated at 11 0MW for 26 hours, and the Hutorf delivers 290MW for 2 hours.

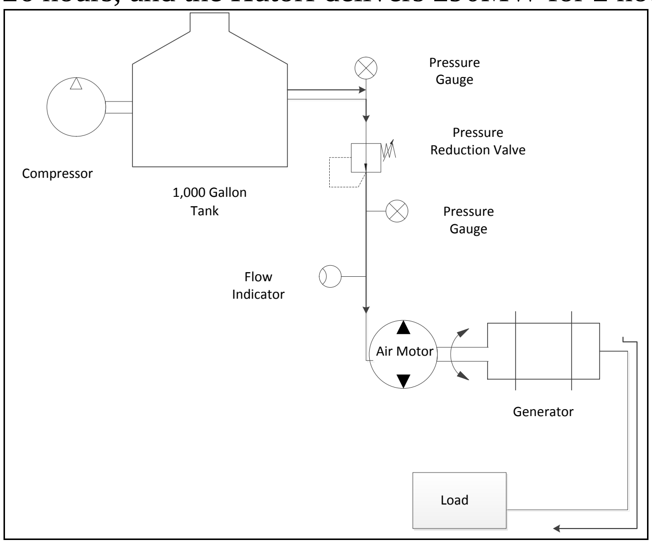


**Figure1.3**: 2010 Pilot System Schematic.

iCAST's CAES model for 2010 is focused on decreasing the reliance on utilities by allowing the storage of energy during off peak hours. This year's pilot will build upon the success of the prototype (2007 CDA-ACRE grant) which was developed in partnership with the University of Colorado Boulder and Colorado School of Mines. An underlying requirement of the iCAST CAES pilot is to provide an affordable storage solution utilizing “off the shelf” parts to make it easy and cost-effective to commission, operate, and repair the equipment

Research will be conducted on the cycle of the system and optimal operating parameters will be evaluated. Testing of the system will be in house and be comprised of input vs. output power, fluid flow, efficiency and constraints where it will be fiscally applicable.

**Figure1.4**: 2010-2011 Small scale compressed air energy storage system.

## Goals and Objectives:

- Storage of compressed air during off peak hours.
  - Satisfaction of safe operating pressure.
- Generation of electricity during peak power prices.
  - Measure electrical input and output.
- Demonstration of system compressing air and generating electricity.
- Control system.
- Prove/refute monetary feasibility.
- Research larger sized CAES systems and implementation feasibility

## Constraints:

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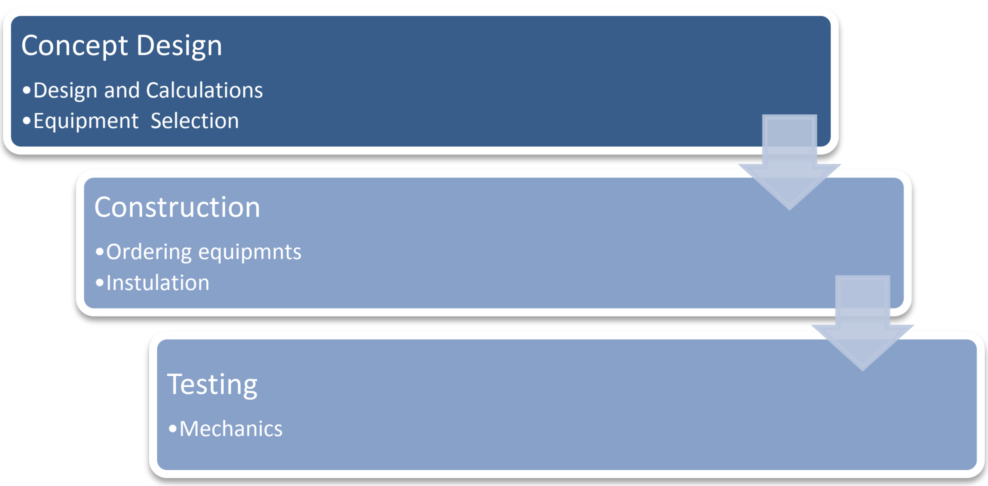
- The CAES unit will have an output power of at least 100 Watts.
- The CAES unit will run for at least 15 minutes.
- Uses off the shelf parts.
- Will not freeze due to low operating temperatures.
- The CAES unit will have safety guards around all moving parts.
    - The CAES unit will comply with any and all safety regulations laid out by OSHA. [OSHA Section 1910 sub-parts H and M pertaining to pressure vessels storing compressed gases including compressed air]
    - The CAES unit will not freeze due to low operating temperatures produced by the rapid expulsion of compressed air.
    - The CAES unit will adhere to any and all Colorado State University codes and regulations pertaining to safety and electrical wiring.

### Criteria:

- The CAES unit should provide a working model that illustrates economic feasibility of a practical real world application.
- The CAES unit should save money during peak time.
- The CAES unit should have an efficiency of greater than 2%.
- The CAES unit should have a clean and easy to work on appearance.

## <u>Layout of plan:</u>




*Full schedule of the design process can be found in the appendix.

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## Problems encountered and/or mitigating circumstances:

- ***Tank Certification***

The tank was the main obstacle toward the leading steps for this project; the holding pressure will affect this design and the calculations. The way this problem was encountered was by contacting with different companies experienced in this matter. Certain companies wouldn't risk doing the test, because of its size, rustiness, and the date it was manufactured; others just assisted with suggestions and estimates on what working pressure the tank can stand.

They only solution was to run the tank on 150 psi, without doing the hydro testing on the tank.( according to Junior "CSU faculty member in foothills laboratory , AirGas who advised us to contact Bud )

- ***Operating conditions***

Operating conditions are the critical part of the calculations. Using a spreadsheet, decision matrix, and actual testing will guide us through calculations in order to reach the highest efficiency possible.

# Design:

Specifications for the compressed air energy storage (CAES) systems were constructed around research conducted at the beginning of the project. The system created at the University of Colorado at Boulder was researched and inspected so that realistic goals could be set for the larger scale CAES system. Basic design choices made by the team at CU were believed by this team to be crippling to the performance of the system. For instance, the system created by CU bled the excess air out to the atmosphere from the turbine. It was an immediate decision made by the CSU team to create a system that would utilize all of the air stored rather than let it blow off. In realizing the power output of CU's system in accordance with its size the CSU team decided that the 1000 gallon tank would be able to store energy for a system that could produce 100 watts of electrical power for at least ten minutes. Further specifications were produced by iCAST, the company funding the design project. The team was to use only parts that were purchased off the shelf and not to fabricate any of the components themselves. The team was also to power some sort of electrical load by the CAES system in order to demonstrate its power and functionality.

An inherent competitive attitude toward CU also helped drive the creation of target goals and specifications. The team at CSU wanted to not only surpass the 50 watts of electrical power that CU achieved, but create a system so superior that 50 watts became negligible. While there was no competition for the CAES system to compete in, the CSU team held the CU system as a benchmark to beat.

The initial concepts of the system revolved around different component combinations that were thoroughly researched and analyzed. There were talks of using many types of generators including AC motors, DC motors, and vehicle alternators. The decision to use a DC motor came from a decision matrix created to weigh the importance of various technical aspects of the generator. The air motor was chosen from a similar process however an excel spreadsheet was created to calculate the run time and torque for optimal running speeds as laid out by the manufacturer. The specific DC motor was then selected based on the output torque and speed of the air motor. The regulator was selected based on its ability to regulate a pressure as great as the 150 psi stored in our tank down to the 15 psi operating pressure required by the air motor. The regulator was also selected because it did not bleed the excess air to the atmosphere.

The piping for the system was another major design aspect that was debated amongst the group. Many options were considered including PVC, ABS, nylon tubing, high pressure air hose, and copper pipe. The decision to use copper was because it was readily available at the greenhouse and its ability to withstand low temperatures created by the flow of air within. Cracking under high pressure combined with frigid temperatures was a large concern regarding the plastic pipes.

The components were analyzed in various mathematical programs in order to determine how well they would integrate with each other. Specifications such as operating speed, torque, power production, and temperature resistance were considered when choosing the best component. It was determined that the copper pipe would withstand the operating pressures and temperatures, the regulator would be able to handle the pressure reduction while holding pressure, and the air motor mated with the DC generator would be able to effectively integrate with each other at ideal operating speeds. It was after this analysis that the parts and components were purchased.

The group was focused on building upon the success of the prototype (funded by the 2007 CDA-ACRE grant) which was developed in partnership with the University of Colorado Boulder and Colorado School of Mines. An underlying requirement of the iCAST CAES pilot is to provide an affordable storage solution utilizing “off the shelf” parts to make it easy and cost-effective to commission, operate, and repair the equipment. So the group visualized the cycle of the system along with the best operating parameters.

A 1.4hp electric air compressor, which is the one CU was using, was used to fill a 1000 gallon tank, which is located at the greenhouse.

| | Weight | Old tesla | GAST 2AM | GAST 6AM | Car supercharger |
|---|---|---|---|---|---|

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| | | | | | |
|---|---|---|---|---|---|
| Cost | 10 | 10 | 6 | 4 | 3 |
| Ease of use | 4 | 4 | 8 | 8 | 2 |
| Availability | 5 | 10 | 10 | 10 | 5 |
| Size | 2 | 8 | 7 | 7 | 7 |
| Safety | 7 | 5 | 7 | 8 | 4 |
| Runtime * Torque | 10 | 3 | 5 | 9 | 5 |
| Max power output | 2 | 3 | 7 | 9 | 6 |
| Total | 40 | 6.33 | 6.73 | **7.50** | 4.18 |

With the current weights of the above decision matrix the 6AM air motor from GAST was the logical selection after debate. Using datasheets from the manufacturer GAST and the ideal gas law, the team calculated which air motor would yield the most power over time under the constraints of the project. The data sheets from GAST provided curves of motor performance at different operating speeds and also efficiencies under certain air pressures. For each of the air motors in our price range the team entered data from the three graphs into a spreadsheet (77 different configurations). The spreadsheet was then programmed to calculate power output, runtime, kWh and potential savings. Each of these values are approximated, assumes there are no losses and the fluid is ideal. We are aware this assumption in unrealistic but was sufficient for our method of choosing the proper air motor to be put in our system.

Generator selection was made through a decision matrix to determine a combination of components that best fits the resources. This decision matrix has different types of generators versus the ease of implementation, availability, reliability, and the cost. By looking at table, the DC motor has the highest value but not substantially over the other AC choices. We then debated that implementation would be a key factor in our design and that the DC motor would be the easiest to integrate into our system.

| | Weight | AC Induction Motor | AC 3-phase motor | DC motor | Vehicle alternator |
|---|---|---|---|---|---|
| Cost | 10 | 9 | 8 | 8 | 9 |
| W/rpm | 7 | 7 | 7 | 6 | 3 |
| Amperage | 5 | 5 | 5 | 5 | 5 |
| Ease of Implementation | 6 | 5 | 6 | 8 | 3 |
| Availability | 6 | 9 | 6 | 7 | 9 |
| Reliability | 8 | 5 | 8 | 8 | 5 |
| Total | 34 | 288 | 290 | **301** | 248 |

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After selecting an air motor the group could then size a motor to be run in reverse as a electrical generator. The group found that an Iron Horse MTPM-P75-1M18 DC motor would operate with the same amount of torque and shaft speed produced by the air motor.

Since our air motor needs to run at a smaller pressure than stored, a regulator was used to reduce the pressure down to our needs. A R119-06DK regulator was chosen due to the fact that this style of regulator doesn't bleed air when reducing the pressure. We could not afford to lose air pressure due to the fact that our efficiency is low enough.

The piping has a huge effect on the system, so research was done to figure out which material would be the most suitable to our design. A list was made to see which can stand the lowest flow temperatures, highest flow pressure, along with safety, price and advantages versus disadvantages of type. Finally, the group decided to use copper pipes for the entire system due to the low working temperatures, and the advantages they have

| | Minimum working temperature | Safety | Advantages / Disadvantages |
|---|---|---|---|
| Polyethylene | Up to -40 F | Safe | -Water applications |
| ABS | Up to -42 F | Not safe with high pressure | +low temperature conductivity<br>+Cheap<br>-May explode<br>-Pigments might be used to prevent it from ultraviolet radiation or painted with a water-base latex paint |
| Vinyl | Up to -33 F | Not safe | -low max pressure<br>-water applications |
| PVC | Up to 0 F | Not safe | +low temperature conductivity<br>-Slip joint problem |
| Copper | Up to -40 F | Safe | +Easy to assemble<br>-High temperature conductivity |
| Steel | Up to 0 F | Safe | -Expensive |
| Galvanized | 0 F | Safe | -Contain lead<br>-Corrode quickly |

Manufacturing took place after receiving all the parts. A stainless steel base was mounted on the side of the tank. Holes were drilled using electric drill using a center drill, 5/32", ¼", 5/16", 3/8" drill bits and soluble oil. After that, the air motor and the generator are attached to the base. The pipe parts such as T connectors and elbows were attached to each other using flux and solder. ¾" copper pipe was cut to size using the pipe cutter and attached from the tank to the regulator. A ½" copper pipe is attached from the regulator to pressure gauge and air motor using a T connection. Once the air motor and the generator are aligned and mounted to the base, a 5/8" keyed coupler is used to attach them to each other. Resistance in the form of 300 watts worth of light bulbs in series was attached to the generator as a load for the power produced.

Quick connects were attached to the compressor and tank. This was implemented so that a different compressor could be attached to the tank if needed. To check for leaks of our 1960's $CO_2$ tank, we filled it to 40 psig and used soap bubbles and an overnight pressure data acquisition gage to insure our tank could be properly used.

The group has successfully assembled a working CAES unit with off the shelf parts. It was tested under multiple settings and conditions to obtain a maximum efficiency of 2.875% with a 320W of power sustained for over 15 minutes, both are more than what it is been written in the constraints.

## Impact:

In a project such as this safety must be kept at all times due to the dangers that could occur if improperly built. Even on a small scale such as the one we were dealing with the pressures were high enough to cause harm so steps need to be taken to minimize the risk. The bigger the system gets, the more stress needs to be put on the safety procedures that encompass it. Future design will make use of unused or abandoned underground caverns and using such a storage unit brings with is great pressures. Evaluating the structure of the cavern will be impeccable in creating a "tank" that can withstand the allowed pressures.

With a larger storage unit comes a larger air motor to spin. A turbine or series of turbines will be implemented and the vane speeds can get easily get into the thousands of rpms which brings with it a huge danger. Much research needs to be put into the turbines to insure they can withstand the pressures introduced, the temperatures that will be reached, and run adequately for the specified time. The temperature of the expanded air gets very cold and the possibility of the system freezing due to condensation is a very big concern. An air dryer and oil drip system are accessories that we learned need to be added to our system but only after completion of our project. The air dryer allows for condensation to be removed from the piping and removes the freezing issue from the components. The oil drip is a necessity for the air motor since the vanes need to be constantly lubricated and with so much air flowing through the motor these vanes get dried out very rapidly. These are just a few upkeep and maintenance issues that need to be addressed when design such a system. If the system isn't maintained properly the functionality and safety of the system will not be kept and failure could be catastrophic. As the rest of the system continues to grow so does the electrical generation and with it large safety concerns. The amount of power produced could be lethal so proper insulation and load paths need to be put in place.

Environmental concerns area an issue for any project and ours is no different. With the introduction of caverns or voids to our system it is important to decide whether or not it will have a negative affect on its surroundings. For our system, unless there is any damage done to the inside surfaces of the cavern which weakens its structural integrity, then there won't be any harm in doing so.

The power production of our system is where some concerns might arise. Our air motor will not be an issue since the exhaust it produces is simply air, free of pollutants to worry about. The initial power generation whether it be electrical, wind turbine, or hydro powered needs to be addressed appropriately. If the system uses wind or water turbines then the impact on the environment becomes relevant. Each of these could pose as a hazard to wildlife and needs to be installed with their safety in mind.

This proof of concept small scale CAES aims to educate and spark the interest of society. The means to produce and store alternative energies is growing everyday and our project displays one way that this storage could be achieved. Our energy demands will only continue to rise and the need for reusable technologies is more necessary than ever. This system has seen public approval and is hopefully educates society that we only have a limited amount of resources in our world and something needs to be done to try and stray away from the finite stock of fossil fuels that we have.

## Conclusion:

Energy costs have been rising immensely over the last couple of years. Power companies charge a "peak demand rate" for a set amount of time daily. During this "peak demand rate" electricity costs high more times than the rest of the day. In addition, the team needs to reduce the amount of money a company spends on energy at that particular time of day. If electricity can be stored and retrieved in an efficient enough manners, then a company can subsidize their electricity from the grid with energy stored on site. Depending on the difference between normal electricity costs and peak demand costs money can be saved.

Furthermore, the challenging part of this problem is how to store this energy in order to use it during peak demand rate, and make it economically feasible. Additionally, the team is looking for a green alternative source of energy that can be stored and used in homes, schools, and agricultural amenities. Also, to prove or refute that a CAES system would be sensible to cut peak electricity costs for a small to medium size consumer.

- The team has designed and constructed a system prototype which stores energy in the form of compressed air; converting said energy into electricity and providing analysis for economic feasibility as well as the best energy storage solution to CSU and iCAST.
- The prototype consists of a compressor that pressurizes air into a storage tank; from there the air will be released through an air motor that will turn a shaft connected to a DC motor. Electrical power will be created by spin the DC motor.
- The team has set the output power to at least 100 Watts running for 15 minutes. Off the shelf components will be used so the system could be easily replicated.
- The system will store compressed air during off peak hours, and generate electricity during peak hours.

## Preliminary findings and key accomplishments:

- ✓ Successful assembled system with off the shelf parts.
- ✓ Tested system under multiple settings and conditions to obtain a maximum efficiency of 2.875%.
- ✓ Produced 320W of power sustained for over 15 minutes.
- ✓ Production of 0.185 kWh during single test.
- ✓ Analysis of larger scale systems using model.
- ✓ Large Scale programmable model was compared to tested data with a 6% calculated error.
- ✓ Payoff analysis including maintenance estimates where calculated.

Accomplishments where successfully achieved, using actual testing data.

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- No parts were built, all where spec'd out to operate at desired conditions
- Total Production Power and running time was calculated using test data: power vs. time
    - This Graph is provided in the Appendices
- Efficiencies were calculated using $\frac{output\ power}{input\ Power} = \frac{0.185\ kWh}{6.5\ kWh} = 2.75\%$
- Matlab Profile is included to demonstrate larger scale operating conditions.
- Economic feasibility analysis including Total annual savings and Annual maintenance is provided in the appendices
    - Showed a yearly savings of $170.23 "Ideal peak time conditions"

# Recommendations:

Based on the research and testing we have done, we feel that CAES is economically feasible if peek prices are greatly higher then off-peak prices. We found that the higher the faction between peek and off-peak price, the greater the return on the system. This is due to the intrinsic assumption that the system will be filled on off-peak electricity and then run during peak time, thus reducing the electricity charges of the user.

A system of the scale we produced is not very efficient and to get any short term payback peaks must be shaved perfectly (which is hard to accomplish in most applications.) To improve efficiency there are a number of immediate solutions. First is to increase the size of the pressure vessel being used. This would cause the system to hold more potential energy and for more air to be discharged through the expander, and thus letting the system run longer. The limiting factor of how large to build a pressure vessel in this situation is how much air the expander will be consuming. There is no purpose with our expander to have a tank 10 times larger then the one we were given, the system would run for much longer than an hour and waste air when peak time was not happening. If a larger tank had been acquired at the beginning of the project, we would have acquired an expander which consumed more air and presumably could run a larger generator thus producing more electricity and shaving more off of peak time, saving more money.

Compressor efficiency generally increases with size. Also we were using a reciprocating compressor but scroll compressors are typically more efficient. If the application called for high pressures then we would recommend selecting a multi stage compressor.

We found that there is not an enormous market for expanders in the size range we needed. We recommend that if a larger scale system was to be designed that the manufacturers in the expander industry were heavily referenced for part selection.

Monitoring electric usage and having the system automated would be key in shaving peek times. We recommend designing an automated system which monitors electrical usage and then operates the CAES system during peak time and fills the tank during off-peak. The system should also monitor temperatures and pressures and have safety protocols to ensure nothing exceeds the proposed limits.

As a final recommendation, any CAES system must be designed within the constraints of a budget. Anyone wishing to design a CAES system must know the constraints of the project before deciding on components (except in situations such as our own, when we knew what pressure vessel and compressor we would be using.)

# Appendices:

## Design Schedule:

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| ID | Indicators | Task Name | Duration | Start | Finish | Prede | Resource Names |
|---|---|---|---|---|---|---|---|
| 1 | | | | | | | |
| 2 | | **FORM CSU Team (Students / John Ray)** | **22 days?** | **Wed 8/18/10** | **Thu 9/16/10** | | **Chris** |
| 7 | | | | | | | |
| 9 | | **Design Phase** | **94 days?** | **Wed 9/8/10** | **Mon 1/10/11** | | |
| 10 | | Initial Design | 24 days? | Wed 9/8/10 | Fri 10/8/10 | | Student Team - CSU |
| 37 | | Initial design due to CSU & iCAST | 0 days | Fri 10/8/10 | Fri 10/8/10 | 10 | Student Team - CSU |
| 11 | | Initial design review approved by CSU - Hort De | 6 days? | Sat 10/9/10 | Fri 10/15/10 | 37 | John Ray - CSU |
| 12 | | Initial design review approved by CSU - ME Dep | 6 days? | Sat 10/9/10 | Fri 10/15/10 | 37 | Syndi - CSU |
| 13 | | Initial design review approved by iCAST | 6 days? | Sat 10/9/10 | Fri 10/15/10 | 37 | Chris / Ravi - iCAST |
| 14 | | Initial design approved and ready for final desig | 0 days | Fri 10/15/10 | Fri 10/15/10 | 13 | |
| 15 | | Final design | 12 days? | Sun 10/17/10 | Sun 10/31/10 | | Student Team - CSU |
| 16 | | Spec out and price Materials | 12 days? | Sun 10/17/10 | Sun 10/31/10 | | Student Team - CSU |
| 17 | | Final design due to iCAST / CSU | 0 days | Sun 10/31/10 | Sun 10/31/10 | 15 | Student Team - CSU |
| 18 | | Identify tools and other equipment required | 11 days? | Mon 11/1/10 | Fri 11/12/10 | 17 | Student Team - CSU |
| 19 | | Draft and create safety plan | 11 days? | Mon 11/1/10 | Fri 11/12/10 | | Student Team - CSU |
| 20 | | Safety plan due to CSU for approval | 0 days | Fri 11/12/10 | Fri 11/12/10 | 19 | Student Team - CSU |
| 21 | | Safety plan review and approval | 10 days? | Mon 11/15/10 | Fri 11/26/10 | 20 | John Ray - CSU |
| 22 | | Safety plan review and approval | 10 days? | Mon 11/15/10 | Fri 11/26/10 | | Syndi - CSU |
| 23 | | Review & approve Equipment price list | 6 days? | Mon 11/1/10 | Sat 11/6/10 | 17 | Chris - iCAST |
| 24 | | Order required materials & equipment | 6 days? | Mon 11/8/10 | Mon 11/15/10 | 23 | Chris - iCAST |
| 25 | | Final approval for construction on facilities | 6 days? | Mon 11/1/10 | Sat 11/6/10 | | John Ray - CSU |
| 26 | | All materials ordered | 0 days | Mon 11/15/10 | Mon 11/15/10 | 24 | Chris |
| 27 | | Equipment lead time | 40 days? | Tue 11/16/10 | Mon 1/10/11 | 26 | |
| 28 | | | | | | | |
| 29 | | **Construction Phase** | **90 days?** | **Mon 1/10/11** | **Fri 5/13/11** | | |
| 30 | | All parts & equipment delivered to CSU green h | 0 days | Mon 1/10/11 | Mon 1/10/11 | | Chris - iCAST |
| 31 | | Pre-construction meeting (safety, rules, access, | 1 day? | Mon 1/10/11 | Mon 1/10/11 | | ALL |
| 32 | | Procure all required tools | 5 days? | Mon 1/10/11 | Fri 1/14/11 | | Student Team - CSU |
| 33 | | Construct system | 41 days? | Mon 1/17/11 | Mon 3/14/11 | 32 | Student Team - CSU |
| 34 | | Demo trail of system (flip the switch) | 0 days | Mon 3/14/11 | Mon 3/14/11 | | ALL |
| 35 | | Work out kinks in the system (tweak) | 44 days? | Tue 3/15/11 | Fri 5/13/11 | 34 | Student Team - CSU |
| 36 | | Final demonstration on project | 0 days | Fri 5/13/11 | Fri 5/13/11 | 35 | ALL |
| 38 | | | | | | | |
| 39 | | | | | | | |
| 40 | | **Progress Report** | **24 days?** | **Fri 10/1/10** | **Fri 10/29/10** | | |
| 41 | | Write progress report | 13 days? | Fri 10/1/10 | Fri 10/15/10 | | Student Team - CSU |

# Appendix A

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| ID | | Task Name | Duration | Start | Finish | Prede | Resource Names |
|---|---|---|---|---|---|---|---|
| 42 | | Progress report due | 0 days | Fri 10/15/10 | Fri 10/15/10 | 41 | Student Team - CSU |
| 43 | | CSU Hort. dept review progress report | 5 days? | Mon 10/18/10 | Fri 10/22/10 | | John Ray CSU |
| 44 | | iCAST review progress report | 5 days? | Mon 10/18/10 | Fri 10/22/10 | | Chris - iCAST |
| 45 | | iCAST review and submit report to CDA | 5 days? | Mon 10/25/10 | Fri 10/29/10 | 44 | Ravi - iCAST |
| 46 | | Progress report submitted to CDA | 0 days | Fri 10/29/10 | Fri 10/29/10 | 45 | Chris - iCAST |
| 47 | | CSU ME Dept. review progress report | 5 days? | Mon 10/18/10 | Fri 10/22/10 | 42 | Syndi - CSU |
| 48 | | | | | | | |
| 49 | | **Final Report** | **70 days?** | **Tue 3/15/11** | **Fri 6/17/11** | | |
| 50 | | Draft final report | 24 days? | Tue 3/15/11 | Fri 4/15/11 | | Student Team - CSU |
| 51 | | Final report draft due | 0 days | Fri 4/15/11 | Fri 4/15/11 | 50 | Student Team - CSU |
| 52 | | CSU Hort. Dept. review final report and comme | 11 days? | Fri 4/15/11 | Fri 4/29/11 | | John Ray - CSU |
| 53 | | CSU ME. Dept. review final report and commen | 11 days | Fri 4/15/11 | Fri 4/29/11 | | Syndi - CSU |
| 54 | | iCAST review final report and comment | 11 days | Fri 4/15/11 | Fri 4/29/11 | | Chris / Ravi - iCAST |
| 55 | | Comments due to students on final report | 0 days | Fri 4/29/11 | Fri 4/29/11 | | |
| 56 | | Work on final draft of report | 10 days? | Tue 5/3/11 | Sun 5/15/11 | | Student Team - CSU |
| 57 | | Final report due to CSU / iCAST | 0 days | Mon 5/16/11 | Mon 5/16/11 | | |
| 58 | | Review and compile other CDA documentation | 25 days? | Mon 5/16/11 | Fri 6/17/11 | 57 | |
| 59 | | Submit final documents to CDA | 0 days | Fri 6/17/11 | Fri 6/17/11 | 58 | |

Appendix A

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## Cost Analysis

| | |
|---|---|
| KHW to Fill the tank | 6.5 KWh |
| Commercial Daily Peak | $ 0.82 |
| Monthly time | $ 2.27 |
| Monthly Filling Cost | $ 4.43 |
| Sum | $ 26.93 |
| Monthly savings | $ 22.49 |
| Yearly Filling cost | $ 52.20 |
| Sum | $ 317.36 |
| Yearly Savings | $ 265.17 |

*Without maintenance calculations

*Data collected from125 PSI blow down test

*Medium to Large scale commercial rates in Fort Collins

## Appendix A
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## Cost of Maintenance

| System Run Time Per Day (hrs) | System Run Time Per Year (hrs) |
|---|---|
| 1 | 365 |

### Regulator

| Run Time Between Servicing (hrs) | Time Between Servicing For This System (yrs) |
|---|---|
| Annually | 1 |

| Cost of Service Kit | Average Cost Per Year |
|---|---|
| $55.00 | $55.00 |

### Air Motor

| Run Time Between Servicing (hrs) | Time Between Servicing For This System (yrs) |
|---|---|
| 6500 | 17 |

| Cost of Service Kit | Average Cost Per Year |
|---|---|
| $140.00 | $8.24 |

### DC Generator

| Run Time Between Servicing (hrs) | Time Between Servicing For This System (yrs) |
|---|---|
| 2500 | 6 |

| Cost of Service Kit | Average Cost Per Year |
|---|---|
| $10.00 | $1.67 |

### Piping Upkeep

| Run Time Between Servicing (hrs) | Time Between Servicing For This System (yrs) |
|---|---|
| Annually | 1 |

| Estimated Cost of Service | Average Cost Per Year |
|---|---|
| $30.00 | $30.00 |

### Total

| Total Annual Service Costs |
|---|
| $94.91 |

Cost of service kits are from local distributors for the components in this system
Time between servicing is from each component's individual datasheet and service manual

# Appendix A

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## Programing Larger Scale sample:

```
clc

S = 0;      %initialize answer array
t=0;        %initialize time
n =0;        %initialize time
rate = 0;   %initialize rate
rate2 =0;   %initialize rate2
kWh_draw = 0; %initialize kwh
pstart = 12.23*6894.757;     %atmospheric pressure, starting pressure
%Charge_Data= 0 ;
%Discharge_Data = 0 ;

gal = 1000;   %tank isze in gallons
%gal=input('How large is the tank? (gallons)  ');
volume = gal*(3.785*10^-3); %converting gallons to m^3

pmax= 70*6894.757;          %max filling pressure
%pmax_psi = input('What is the max fill pressure?  (psi)  ' );
%pmax = pmax_psi*6894.757;
P2 = pstart;
rho1 = 1;                %starting density at 5000 ft = 1500m
mass = volume*rho1;          %starting mass
starting_mass = volume*rho1; %starting mass
ending_rho = (2.7*((pmax/6894.757)+12.23)/(70+495.7))*16.018;
ending_mass = volume*ending_rho;


%the follwoiong are for cost calculations
draw_comp = 1.3;       % electricity usage of compressor in kW
off_peak = 0.022;      % off peak cost of electricity
on_peak = 5.06;        % daily on peak cost of electricity
demand_charge = 13.97; % monthly 15 minute demand charge

disp('begining fill cycle')
while mass <= ending_mass
    t= t+1    ;
    rate = 0.00158*exp(-9*10^-7*P2);
    mass = mass + rate    ;
    new_rho= (2.7*((P2/6894.757)+12.23)/(565.7))*16.018;
    P2 = ((mass*565.7/16.018/volume/2.7)-12.23)*6894.757;
    kWh_draw = kWh_draw + (5*10^-7*t +1.0955)/60/60;

    mass_array(t)=mass;
    rate_array(t) = rate;
    time_array(t)=t;
    pressure_array(t)= P2;
end

fill_time_minutes = t/60 ;
```

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```
fill_time_hours = t/3600 ;
mass ;
P2_psi = P2/6894.757 ;
filling_cost = kWh_draw * off_peak;

Charge_Data.Fill_time_minutes = fill_time_minutes ;
Charge_Data.Fill_time_hours = fill_time_hours ;
Charge_Data.Air_mass = mass ;
Charge_Data.Ending_psi_abs = P2_psi +12.23;
Charge_Data.Ending_psi_gague = P2_psi ;
Charge_Data.Fill_Cost = filling_cost;

Charge_Data
disp ('_____________________________________________');
disp ('begining of discharge cycle');

while mass >= starting_mass
%for ertasdfasdf = 1:10
    n= n+1;
    rate2 = 0.0003*P2^2 - 0.0047*P2 +0.0011;
    mass = mass - rate;
    new_rho = (2.7*((P2/6894.757)+12.23)/(70+495.7))*16.018;
    P3 = (((mass*565.7/16.018/volume/2.7)-12.23)*6894.757);
    mass2_array(n)= mass;
    rate2_array(n)= rate2;
    time2_array(n)=n;
    pressure2_array(n) = P3;

end

%mass
%new_rho
%P3

run_time_minutes = n/60;
run_time_hours = n/3600;
P3_psi = P3/6894.757;
%run_savings = kWh_produced * on_peak;

Discharge_Data.Run_time_minutes = run_time_minutes;
Discharge_Data.Run_time_hours = run_time_hours;
Discharge_Data.Ending_Air_Mass = mass;
Discharge_Data.Ending_psi_abs = P3_psi+12.23;
Discharge_Data.Ending_psi_gague = P3_psi ;
%Discharge_Data.Run_savings = run_savings;

Discharge_Data


%plot(time2_array, pressure2_array)
%hold on
%plot(time2_array, rate2_array)
```

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```
%plot(time_array , mass_array)
%hold on
%plot(time_array, pressure_array)
```

# Appendix A
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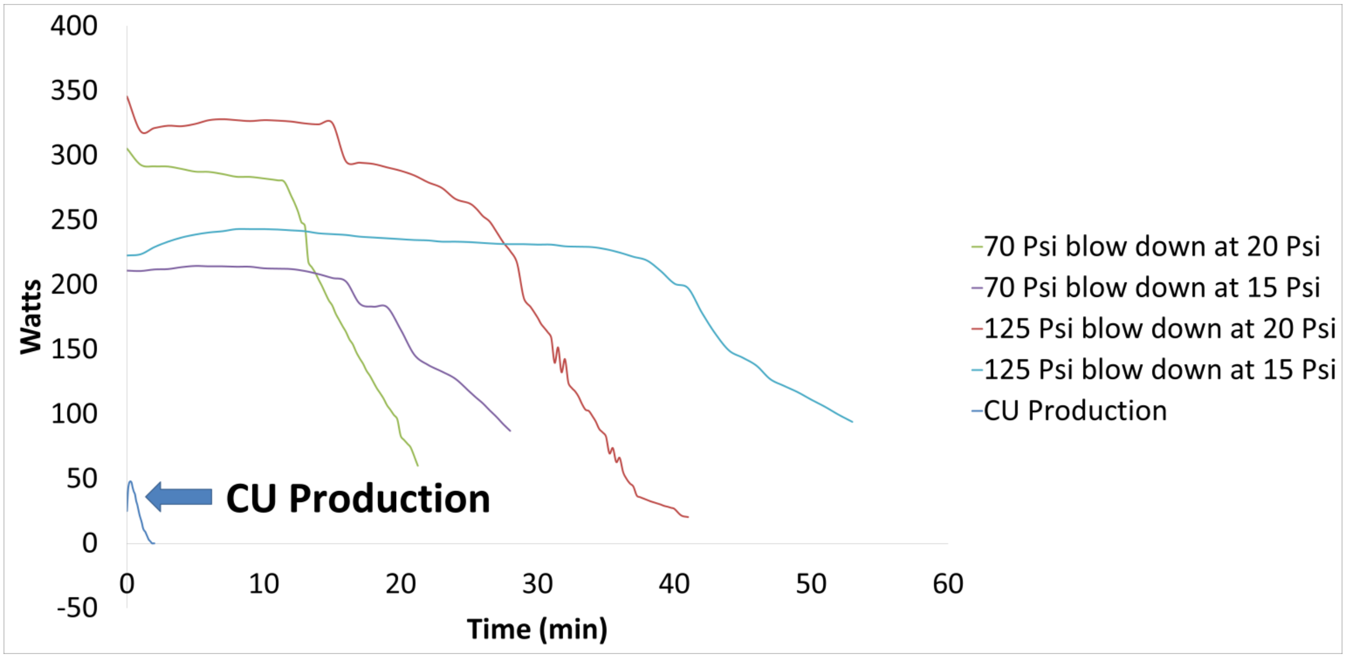
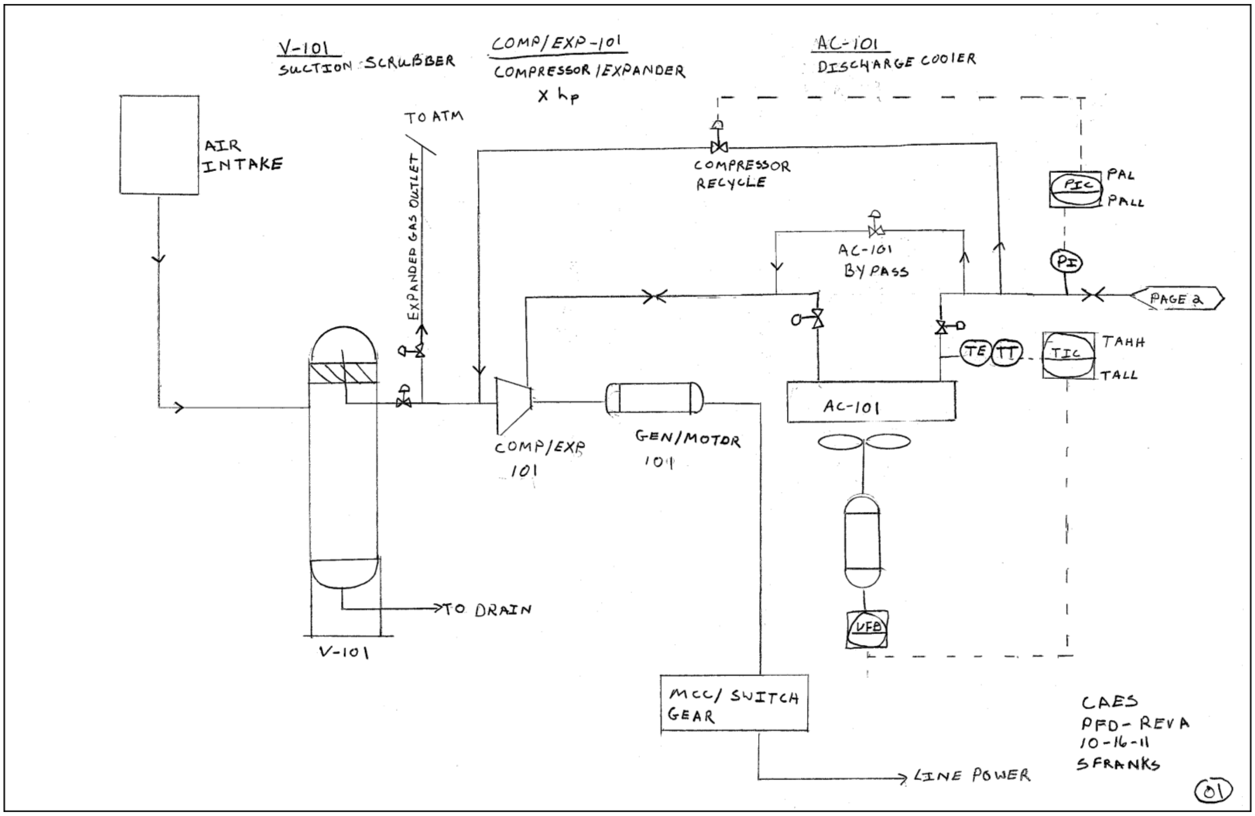
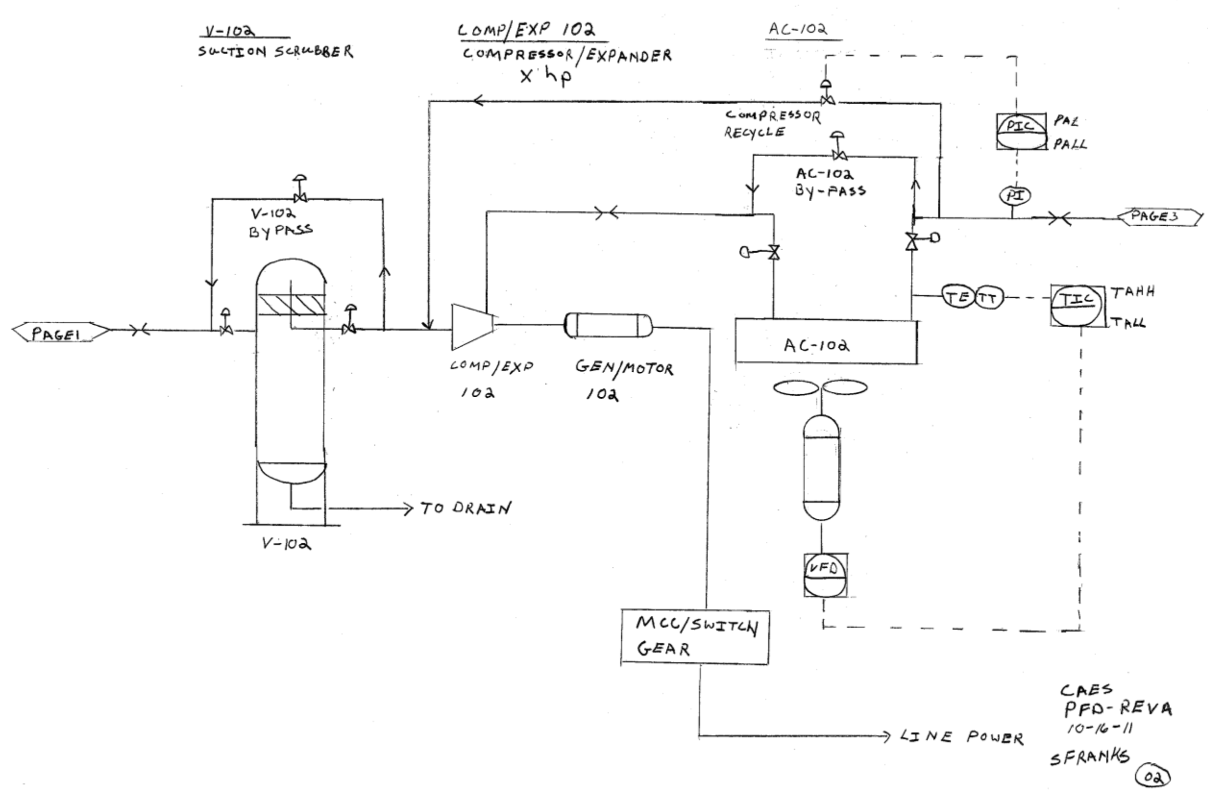
**Power vs. Time**



**Appendix B**
**Process Flow Diagrams**



# Appendix B
# Process Flow Diagrams